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Gamma Exposure Rates Due to Neutron Activation of Soil: Site of Hood Detonation, Operation Plumbbob

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Abstract

This paper is the result of some recent discussions of exposure rates within the first few hours of the Hood detonation of the Plumbbob series due to neutron activation of soil. We estimated the exposure rates from 1/2 to 3 h after the detonation from ground zero to 1000 yards from ground zero. The area was assumed to be uncontaminated by fallout.

Soil samples from the area of the Nevada Test Site at which the Hood device was detonated (see Fig. 1) were sent to ORNL by Dr. John Malik of Los Alamos and by Mr. Gordon Jacks of the Nevada Test Site. These samples were irradiated at the DOSAR facility[1] and the resulting activity analyzed. Calculations of exposure rates were then made based on the analyzed activity and the measured thermal neutron fluences at DOSAR and at the Hood Site.

Geometry and Source Parameters

The Hood shot was a 74 kiloton device detonated at a height of 457.2 m (1500 ft) above the surface of the earth. A description of the shot and the resulting neutron fluences are documented in WT-1504.[2] The exposure rates were calculated for one meter above the surface of the earth; however, the exposure rates changed only slightly from 0.5 meters to more than two meters above the surface. The surface of the earth was treated as an infinite plane source with an activity depth of 30.5 cm (12 in). The methods used for the volume source calculations were taken from Morgan and Turner.[3]

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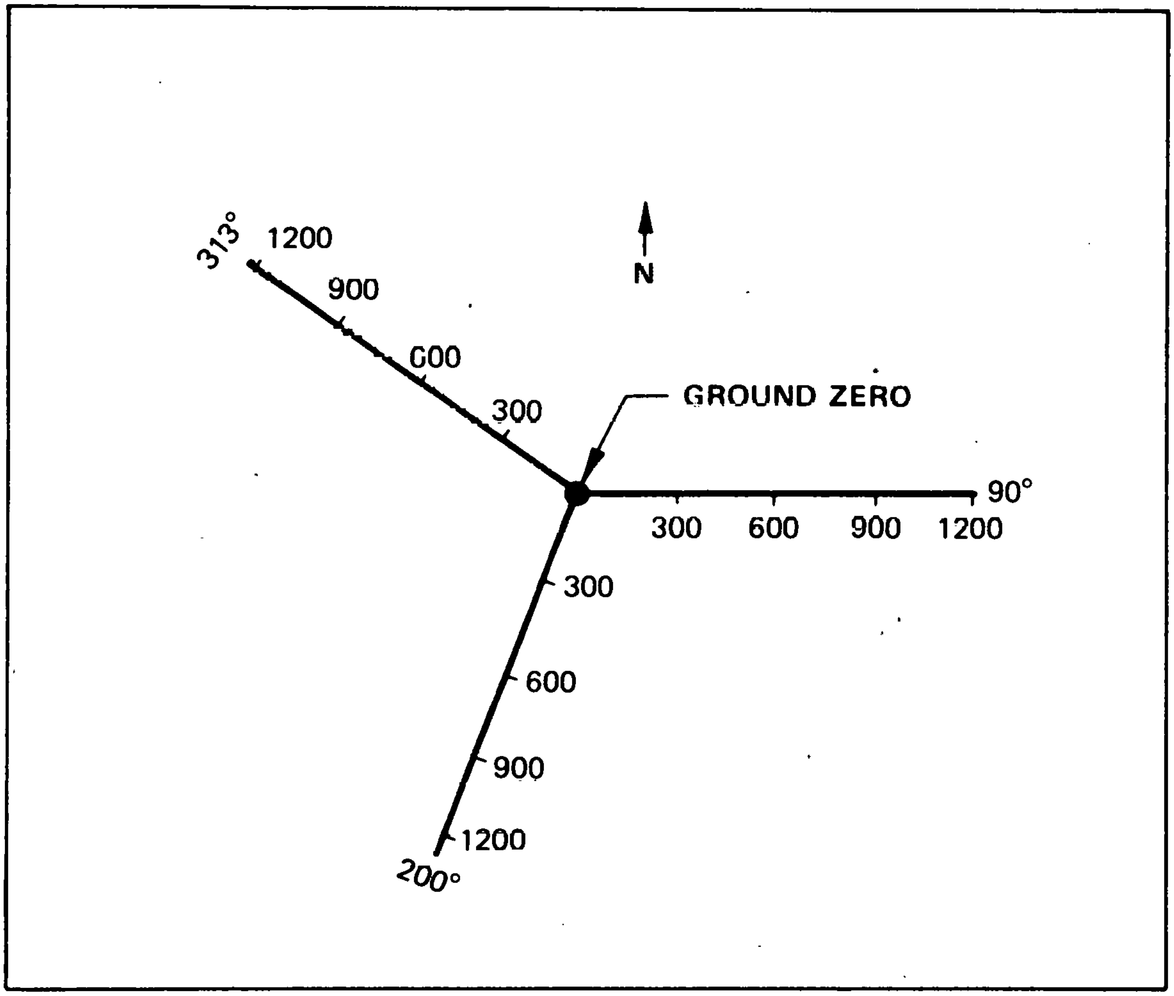

Fig. 1 Soil samples were taken at 300, 600, 900, and 1200 yards as shown on each of the radials from ground zero.

Soil Activity as a Function of Depth

Hood data indicated that the thermal neutron fluence increased from the surface of the earth to a maximum at a depth of 15.2 cm (6 in). Below this depth the fluence decreased and was about the same as the surface fluence at 30.5 cm (12 in). The following variation in soil activity was assumed:

From the surface down to 15.2 cm

$$\text{Activity} = \text{Activity at Surface} \times \left(1 + 0.6824 \times \frac{\text{depth (cm)}}{15.2\ \text{cm}}\right)$$

From 15.2 to 30.5 cm

$$\text{Activity} = \text{Activity at Surface} \times \left(1.6824 - 0.71529\ \frac{\text{depth (cm)} - 15.2\ \text{cm}}{15.2\ \text{cm}}\right)$$

Dose Rate Calculation:

The following formula was used to calculate the exposure rates:

$$ER = \frac{2\pi\ N\Sigma\ n_i G_i}{\mu_{al}}\ [(E_2(\mu_{air} \times d + \mu_{al} \times a) - E_2(\mu_{air} \times d + \mu_{al} \times a + \mu_{al} \times h)]$$

where,

ER is gamma exposure rate in R/h,

N is specific activity in pCi/cm^3,

n_i is the number of gammas per disintegration of energy i,

G_i is specific gamma constant in $\frac{\text{R-cm}^2}{\text{pCi-h}}$ for gamma of energy i,

μ_{al} is the energy absorption cross-section for aluminum in cm^{-1} (the aluminum cross-section was used because it is similar to that of silicon and other constituent elements of the soil),

μ_{air} is the energy absorption cross-section for air in cm^{-1},

d is distance in air from surface to measurement point in cm,

a is thickness of soil above the source slab in cm,

h is the thickness of the source slab in cm.

$E_2(\mu_{air} \times d + \mu_{al} \times a)$ and $E_2(\mu_{air} \times d + \mu_{al} \times a + \mu_{al} \times h)$ are the E functions (discussed in Morgan and Turner, chapter nine[3]). The E functions were calculated using the following series and recursion formula:

$$E_1(b) = -0.5772157 - \ln(b) + b - \frac{b^2}{2\times2!} + \frac{b^3}{3\times3!} - \cdots\cdots$$

$$E_2(b) = e^{-b} - bE_1(b)$$

Since the activity is assumed to vary with depth, the top 30.5 cm (12 in) of soil was divided into 24 slabs each 1.27 cm (0.5 in) and the exposure rate was calculated separately for each layer (see Fig. 2). The exposure rates from the layers were summed to give the total exposure rate.

The activity of the soil at the surface per unit thermal fluence was assumed to be equal to that obtained by the DOSAR irradiation per unit thermal fluence and normalized to zero decay time. The relative exposure rates from the predominate gammas are shown in Table 1. The thermal fluence due to the DOSAR irradiation was 5.01×10^{11} neutrons/cm^2. The exposure rate at the site was calculated by using the following relationship:

$$\text{Hood exposure rate at zero decay time} = \text{DOSAR exposure rate} \times \frac{\text{thermal fluence at Hood Site}}{5.01 \times 10^{11}}$$

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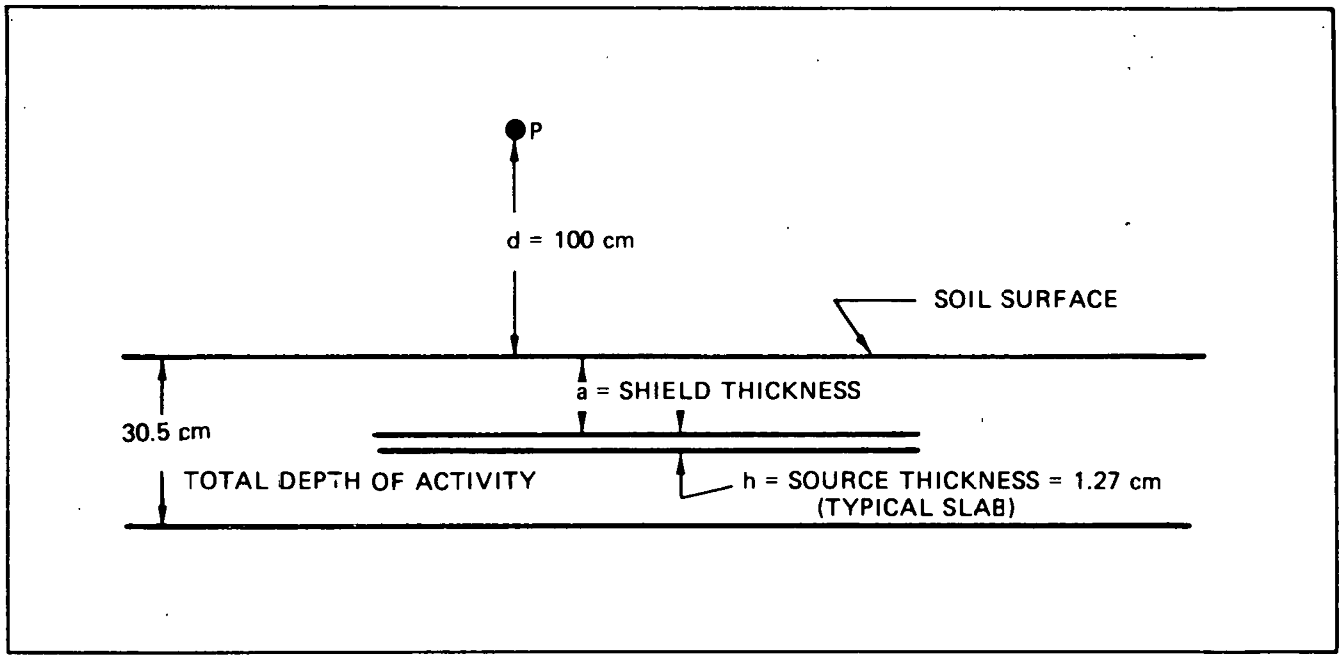

Fig. 2 GEOMETRY FOR CALCULATING EXPOSURE - Rate at Point P
(The activated soil is assumed to have the geometry of a truncated cone with planar surface and a thickness of 30.5 cm.)

Table 1. Exposure Rates Calculated for Individual Gamma Ray Energies Based on Soil Activity from DOSAR Irradiation

Isotope	Gamma Energy (MeV)	$T_{1/2}$	Dose rate in mR/hr at 1 meter above ground as function of time after T_o (in hours)			
			T=0.5	T=1.0	T=1.5	T=3.0
^{27}Mg	0.18	9.5 m	< 1	< 0.1	< 0.1	< 0.1
	0.84		122.3	13.7	1.5	< 0.1
	1.01		63.4	7.1	0.8	< 0.1
^{56}Mn	0.847	2.58 h	13.3	11.6	10.1	6.8
	1.811		8.1	7.1	6.2	3.6
	2.110		5.0	4.4	3.9	2.3
^{38}Cl	1.60	37.3 m	2.3	1.3	0.7	0.1
	2.17		3.8	2.1	1.2	0.2
^{42}K	0.31	12.5 h	< 0.1	< 0.1	< 0.1	< 0.1
	1.524		0.7	0.7	0.7	0.6
^{24}Na	1.369	14.9 h	13.4	13.1	12.8	11.9
	2.754		23.9	23.3	22.8	21.2
^{87}Sr	0.388	2.83 h	0.1	0.1	0.1	0.1
			256.3	84.5	60.8	46.8

The results of the exposure rate calculations are shown in Table 2. These values are more than an order of magnitude lower than those given in DASA 1251 but are in accord with values measured by Project 39 personnel during early recovery of dosimeters, i.e. within the first hour after the detonation.

Some Possible Sources of Error:

1. The density of the undisturbed soil is somewhat uncertain. The density of the crushed samples was approximately 1.4 g/cm^3, but a density of 1.6 g/cm^3 was used in the calculations because it was felt that the undisturbed soil was more dense. We believe that the true soil density lies within the range of 1.6 ± 0.2 g/cm^3. Sensitivity calculations indicate that this would cause less than ± 5% error in the final results.
2. The exact cross-sections were not known and were taken to be the same as those for aluminum. In the range of energies applicable to this problem, the cross-sections for light elements are almost identical. Assuming a maximum of 8% error in cross-section and using a sensitivity calculation, the maximum error in the final results due to this uncertainty is ± 7%.
3. Energy absorption cross-sections were used in the calculations, also we assumed no build-up. A calculation using the simplified assumptions of uniform activity distribution and infinite source thickness indicated a sensitivity of less than ± 1%. when build-up factors and total cross-sections were used.

Table 2. Calculated Gamma Exposure Rates Due to Soil Activation by Hood Device

Distance from Ground Zero (yards)	Slant Range (Yards)	ϕ_{th} Thermal Fluence n/cm^2	Dose Rate in R/hr at 1 meter above ground as function of time after T_0 (in hours)			
			T=0.5	T=1.0	T=1.5	T=3.0
1,000	1,118	3.25×10^{12}	1.7	0.55	0.4	0.3
900	1,029	5.22×10^{12}	2.7	0.88	0.6	0.5
800	943	8.36×10^{12}	4.3	1.4	1.0	0.8
750	901	1.07×10^{13}	5.5	1.8	1.3	1.0
700	860	1.34×10^{13}	6.9	2.3	1.6	1.3
600	781	2.13×10^{13}	11	3.6	2.6	2.0
500	707	3.35×10^{13}	17	5.7	4.1	3.1
400	640	5.16×10^{13}	26	8.7	6.3	4.8
300	583	7.57×10^{13}	39	13	9.2	7.1
200	539	1.03×10^{14}	53	17	13	9.6
100	510	1.27×10^{14}	65	21	15	12
0	500	1.36×10^{14}	70	23	17	13

4. Uncertainty in determining the soil activity was ± 6%.
5. Assume DOSAR fluence accuracy of ± 10%.
6. Assume Hood fluence accuracy of ± 10%.
7. There is some error associated with assuming a uniform infinite plane source. Sensitivity calculations indicated 15% greater dose rate from a source with infinite radius than from a source with a radius of 40 meters (44 yards). At a slant range of 914 m (1000 yards) the soil activity was 30% higher 40 m toward ground zero and 15% lower 40 meters away from ground zero. Since these differences tend to cancel each other, it is felt that the error due to simplified geometry would not exceed 15%.
8. Error caused by assuming no soil activation below 30.5 cm is less than 8%.
9. Sensitivity calculations were made assuming constant activity of the soil from 0.0 to 30.5 cm deep and also made using a half-value of 8.64 cm for attenuation of activity. The results of these calculations were compared with the results obtained which assumed a build-up of activity with depth which reached a maximum activity at 15.2 cm (6 in). These comparisons indicated that the results were not very sensitive to the distribution of activity with depth. The difference in the constant activity model results and the activity build-up model was 29%. The difference between the constant activity model and the one which assumed an attenuation of activity

with soil depth was 15%. Any departure from the build-up model which is based on neutron fluence measurments at the surface, at 15.2 cm (6 in) and a 30.5 cm (1 ft) depth at the Hood Site would probably not change the results more than 15%. If the overall uncertainty in the results is equal to the square root of the sum of the squares of the individual uncertainties, the overall uncertainty is ± 29%.

Conclusions

In the process of checking the effects of the various uncertainties, it became apparent that final exposure rates were not very sensitive to variation in many of the parameters. It seems that reasonably useful answers are obtained even though a number of simplifying assumptions are made. A programmable calculator was of invaluable assistance in making the calculations and testing the sensitivity to variations in the parameters.

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